Study of critical technology items for an Advanced Earth Orbiting Atmospheric Chemistry/Climate Observatory Using Cryogenic Millimeter/Submillimeter Receivers

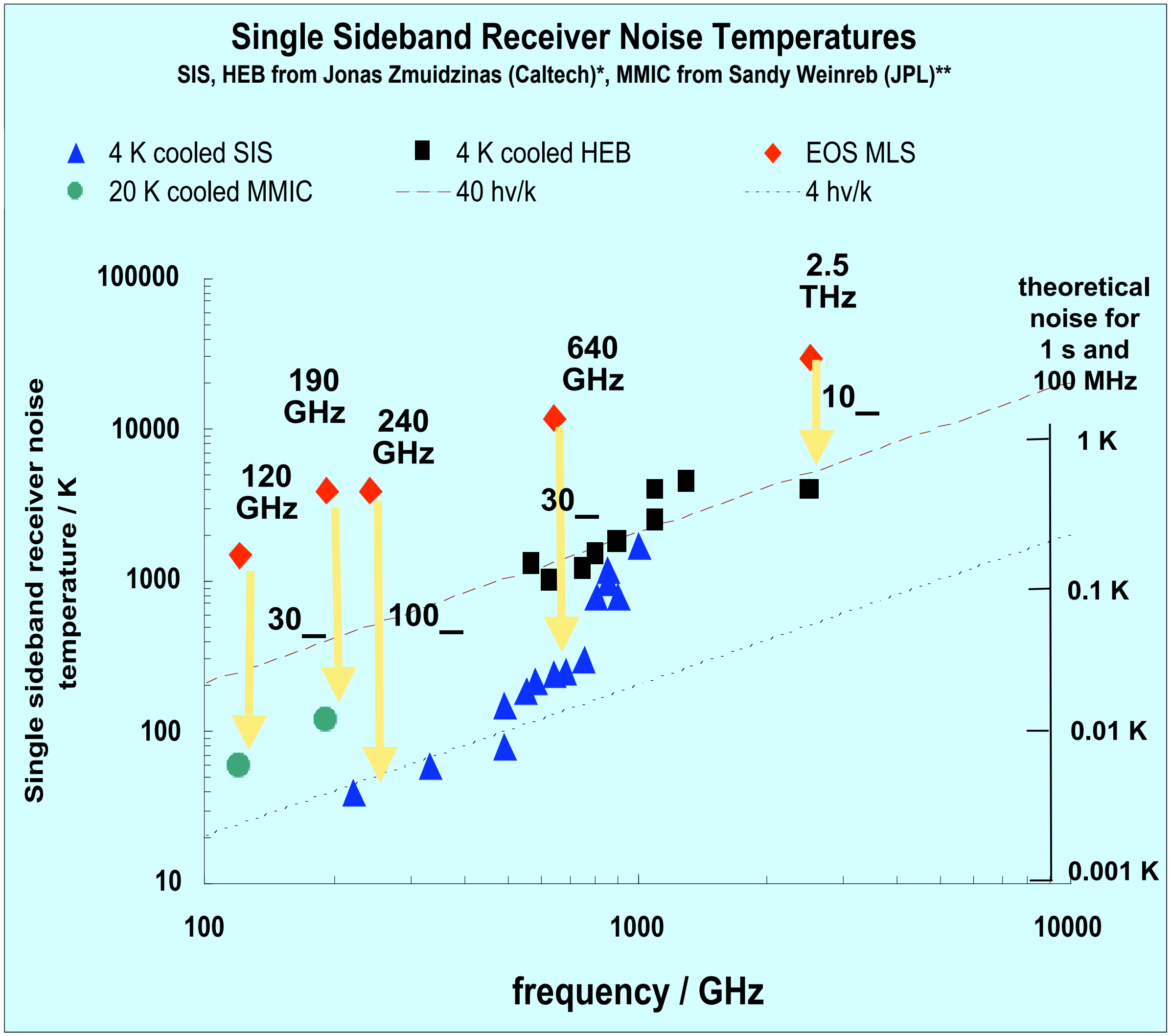
P.C. Stek, J.W. Waters, D.F. Braun, D.L. Johnson,
R.E. Cofield, R.F. Jarnot, M. Santee, R.A. Stachnik
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, Ca 91109-8099

T.T. Cafferty
TC Technology
2022 Cliff Drive #259
Santa Barbara, CA 93109

Can ultra-sensitive, cooled receivers be incorporated in modest sized earth observing instruments?

- **The Promise of Cryogenic Receivers for Earth Observing Systems**
  - 30 fold sensitivity improvement over present space based measurements
- **Straw-man instrument**
  - 5 band radiometer
    - RFE technology - 2 MMIC, 2 SIS, 1 HEB
  - Low DC power requirement
- **Mechanical layout**
  - A structurally viable concept with low parasitic losses
- **Thermal modeling**
  - Heat load distribution to keep spacecraft bus loading for cooling under 200 Watts
- **Example of what can be done with this Technology**
  - A Scanning Microwave Limb Sounder

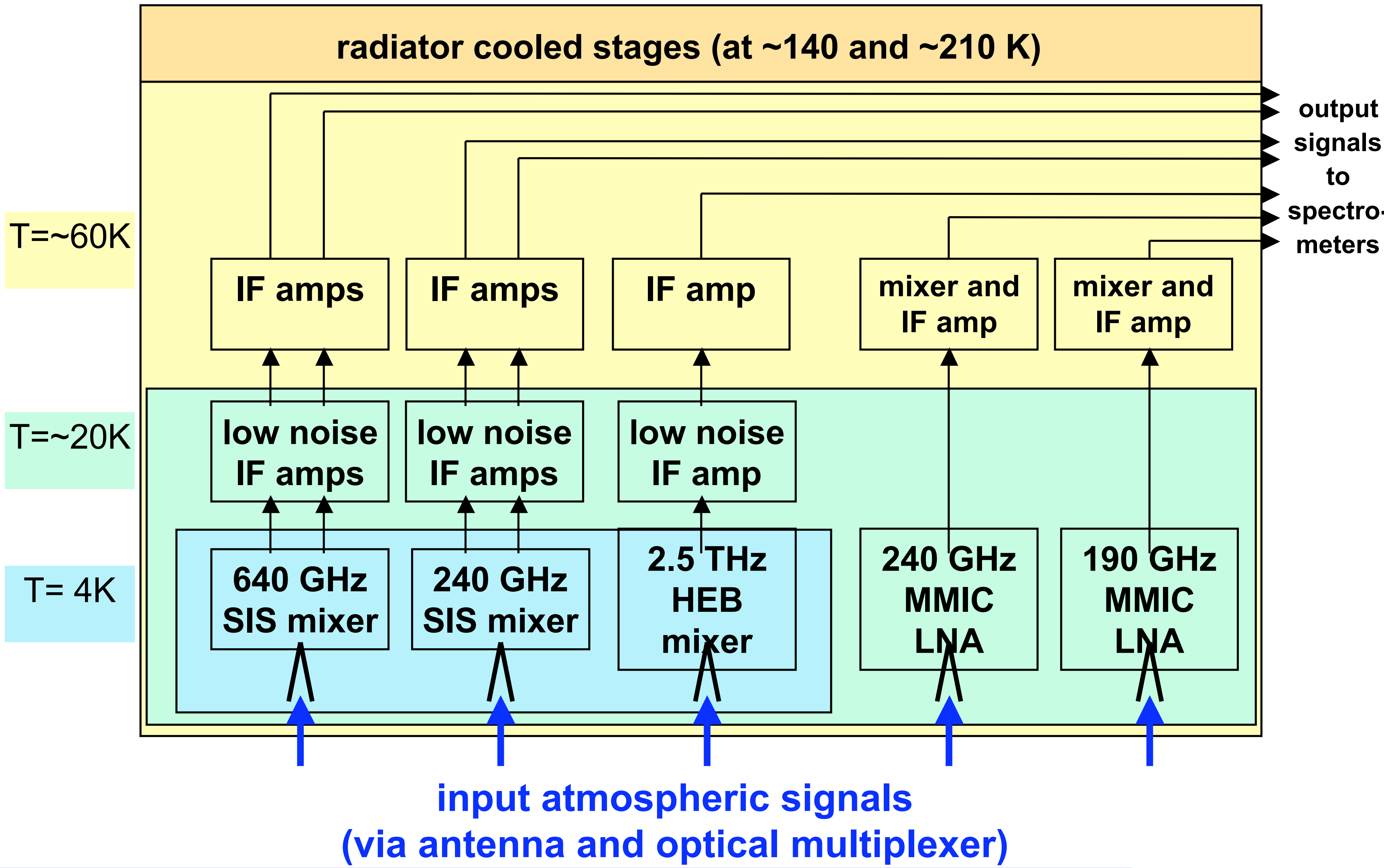
Reduce Integration Time by 900 by Cooling Receiver Front Ends



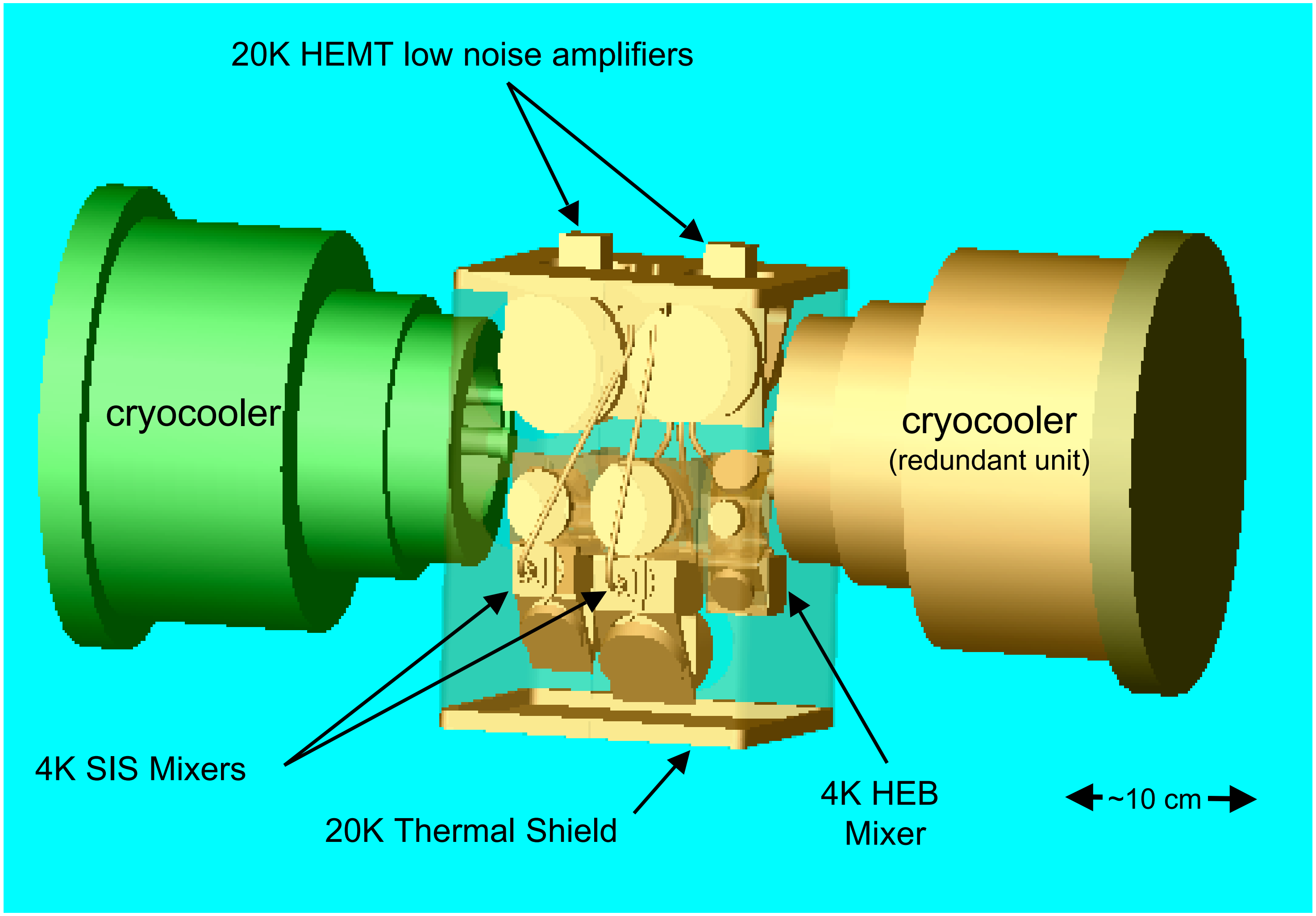
Note: required measurement time decreases as square of the improvement in sensitivity (e.g. 30x sensitivity improvement means 900x less measurement time is required in terms of signal-to-noise, can do in 1 hour what previously took one month, or do in 1 millisecond what previously took 1 second).

Suite of Radiometer Front Ends

SIS = Superconductor-insulator-superconductor; HEB = Hot electron bolometer
MMIC = monolithic millimeter-wavelength integrated circuit LNA = Low noise amplifier

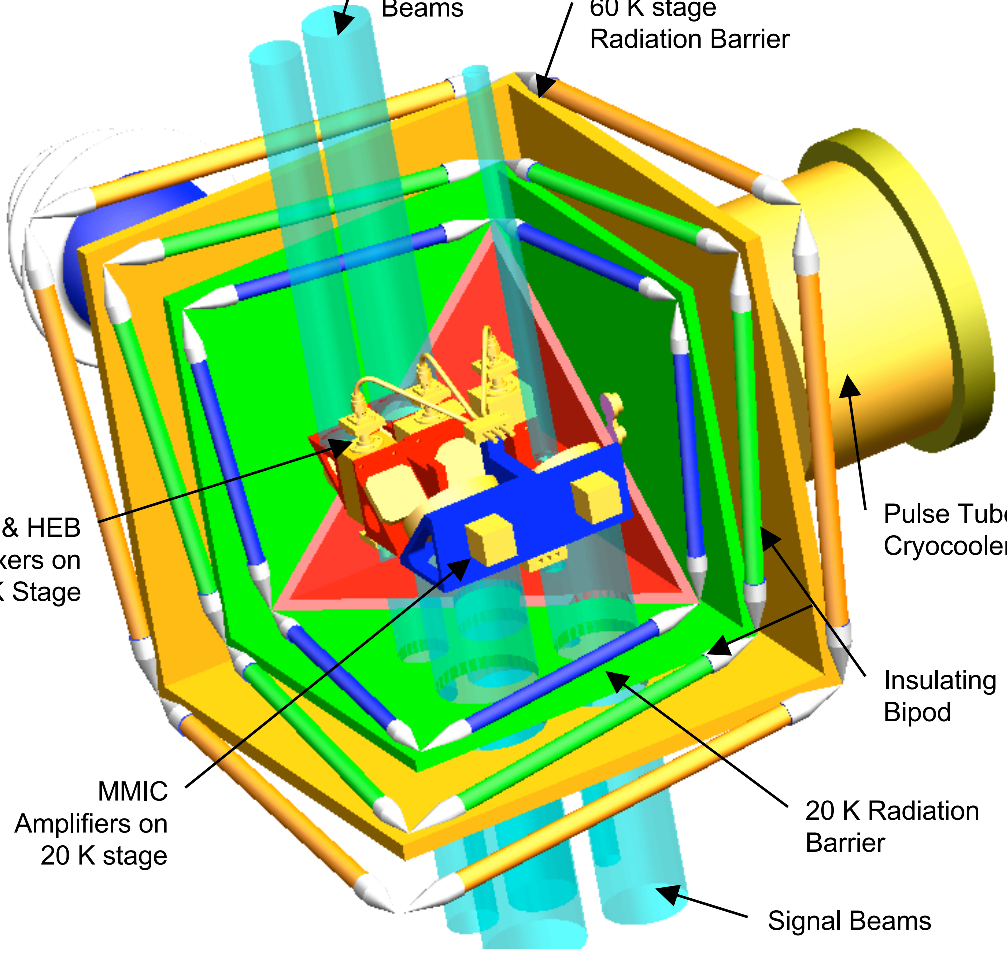


A layout concept for 4 & 20 K stages of cryocooler
(concept option with redundant cryocoolers)



We expect to take advantage of developments underway for 6 K coolers for future NASA Code S missions having flight coolers planned for delivery as early as 2007

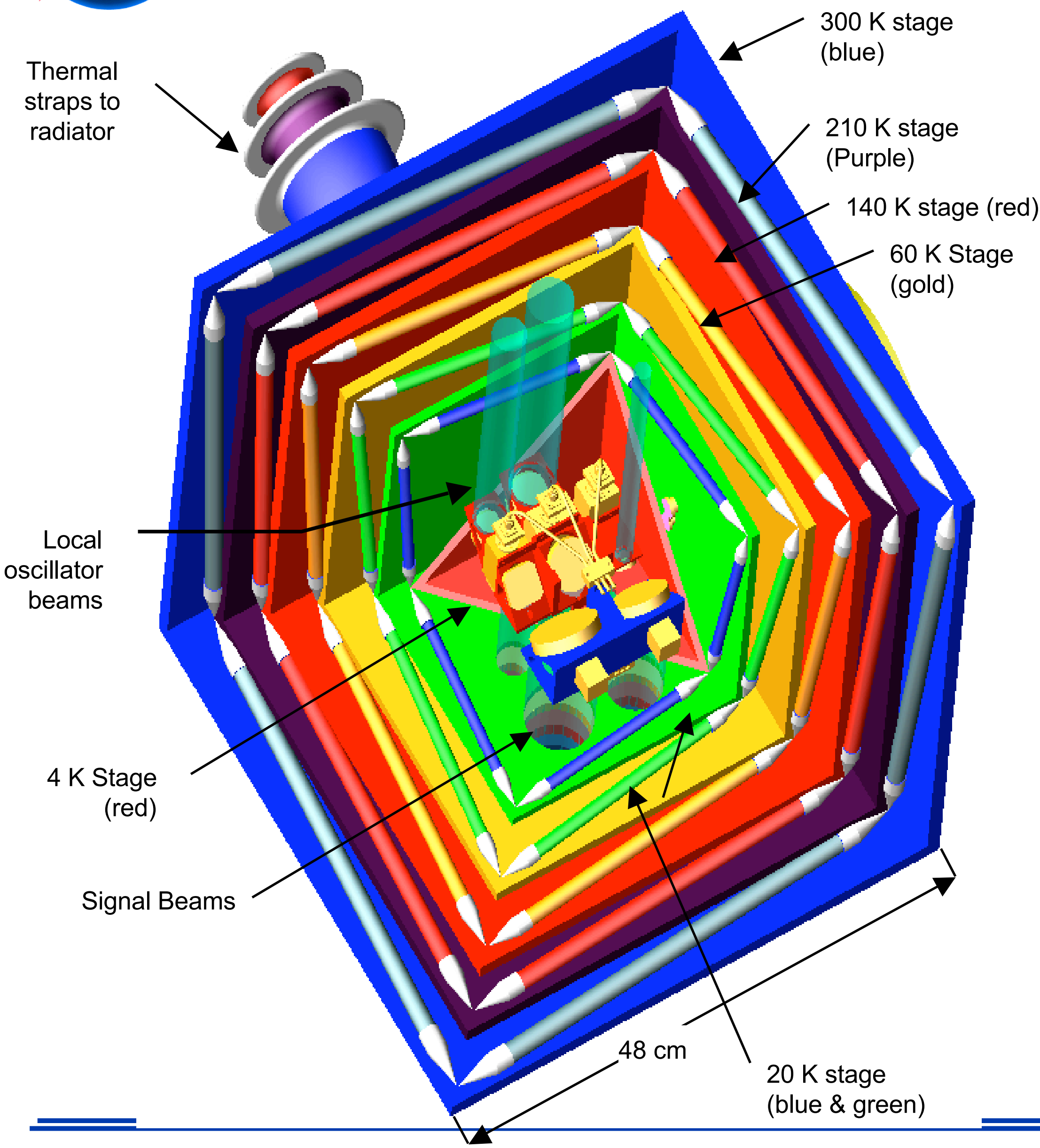
Mechanical Concept 4-60 Kelvin Stages



140-300 K stages, redundant cryocooler and half of 20 and 60 K radiation barriers omitted

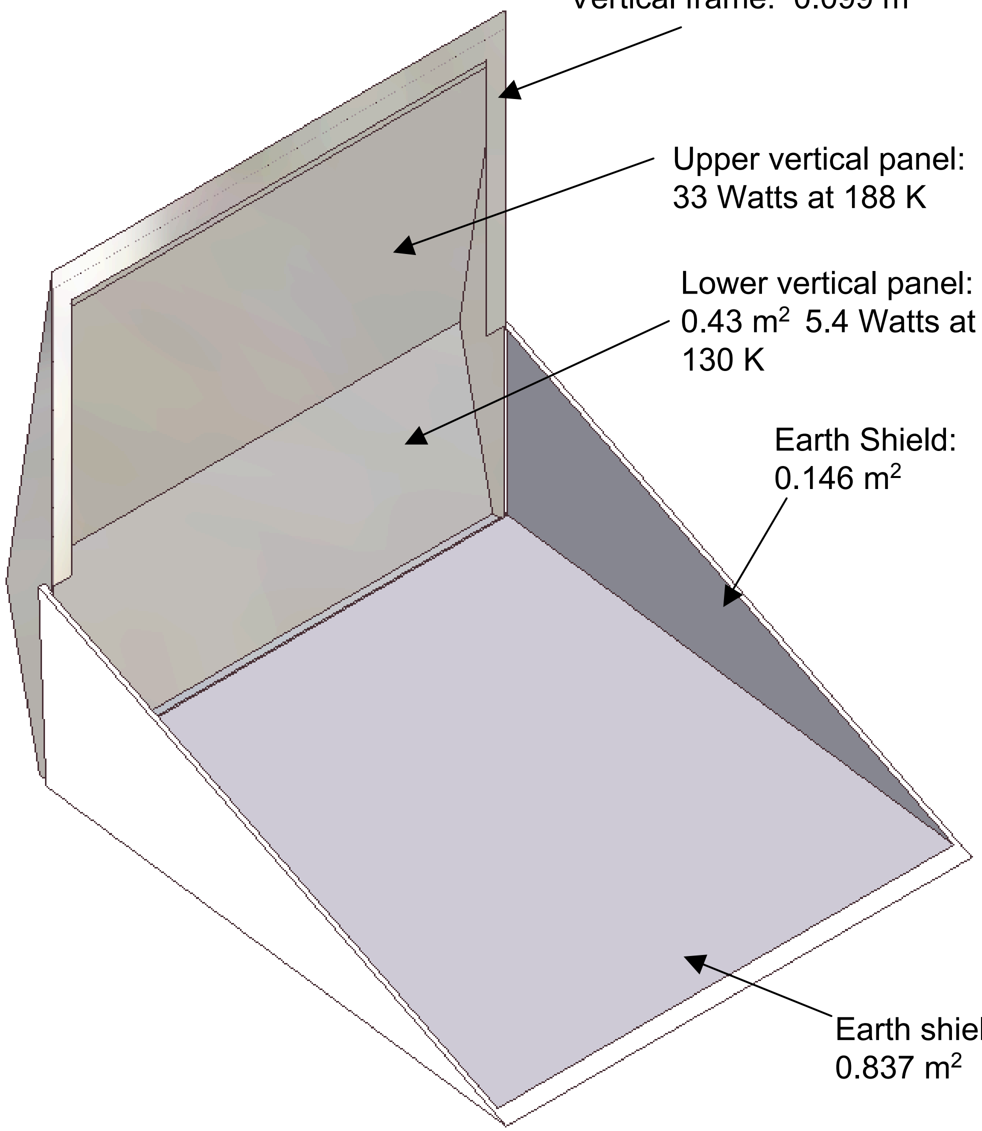
- **3 Bipods support each stage from previous stage.**
  - Ex. Green bipods support the green 20 K radiation barrier from the gold 60 K radiation barrier.
  - Bipods constructed of thermally insulating rods of carbon and fiberglass
- **Radiation barriers built from aluminum isogrids are integral component of support structure.**
- **Only mixers and final optics cooled to 4 K**
- **IF and MMIC amps at 20 K**
- **Local oscillator and signals delivered to receivers quasioptically using parallel beams.**

Concept Used for Mechanical Modeling



- **3 of 6 faces of each radiation barrier and redundant cooler removed in this view.**
- **Structural analysis gives lowest vibrational mode at 140 Hz for full assembly. (Flight hardware usually specified to have no resonances below 80 Hz.)**
- **Cryocooled stages at 60, 20, and 4 K**
- **Radiatively cooled 210 and 140 K stages**
- **Low pass filters at 210 and 60 K for LO and Signal paths to reduce radiation loading on 20 and 4 K stages**

Radiator

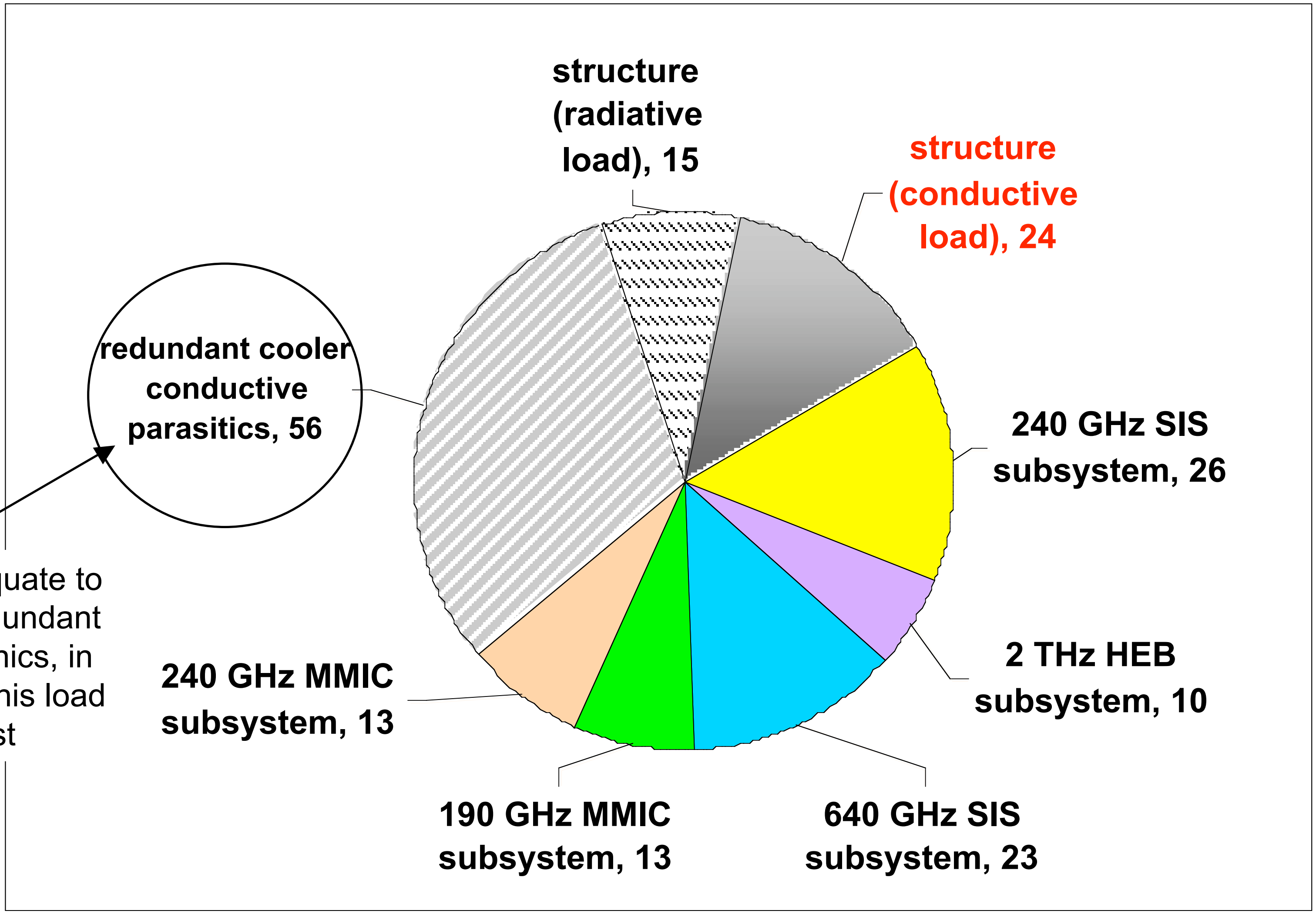


- **Radiative cooling for 140 and 210 K stage**
- **1 square meter**
  (half of this for THz LO)
- **Coolers heat sunk on separate radiator at 300 K**

Estimated Heat Loads

heat load item	cryocooler heat load (mW)			required drive power per item (Watts)	required bus power @ 89% efficiency (Watts)
	4K stage	20 K stage	60K stage		
structure, radiative load	0.8	1.4	216	13	15
structure, conductive load (goal)	2.0	20	80	21	24
redundant cooler	4.4	52	173	50	56
190 GHz MMIC radiometer	0	12	163	12	13
240 GHz MMIC radiometer	0	12	136	10	12
240 GHz SIS radiometer	2.3	21	72	23	26
640 GHz SIS radiometer	2.1	21	34	20	23
2 THz HEB radiometer	0.8	11	18	9	10
TOTAL	12 mW	150 mW	900 mW	160 W	180 W
specific power for each stage	5000	400	40		
drive power per stage (Watts)	60 W	60 W	36 W		
drive power for all stages (Watts)	160 W				
Required bus power with 5 W tare and 89% power supply efficiency	185 W				

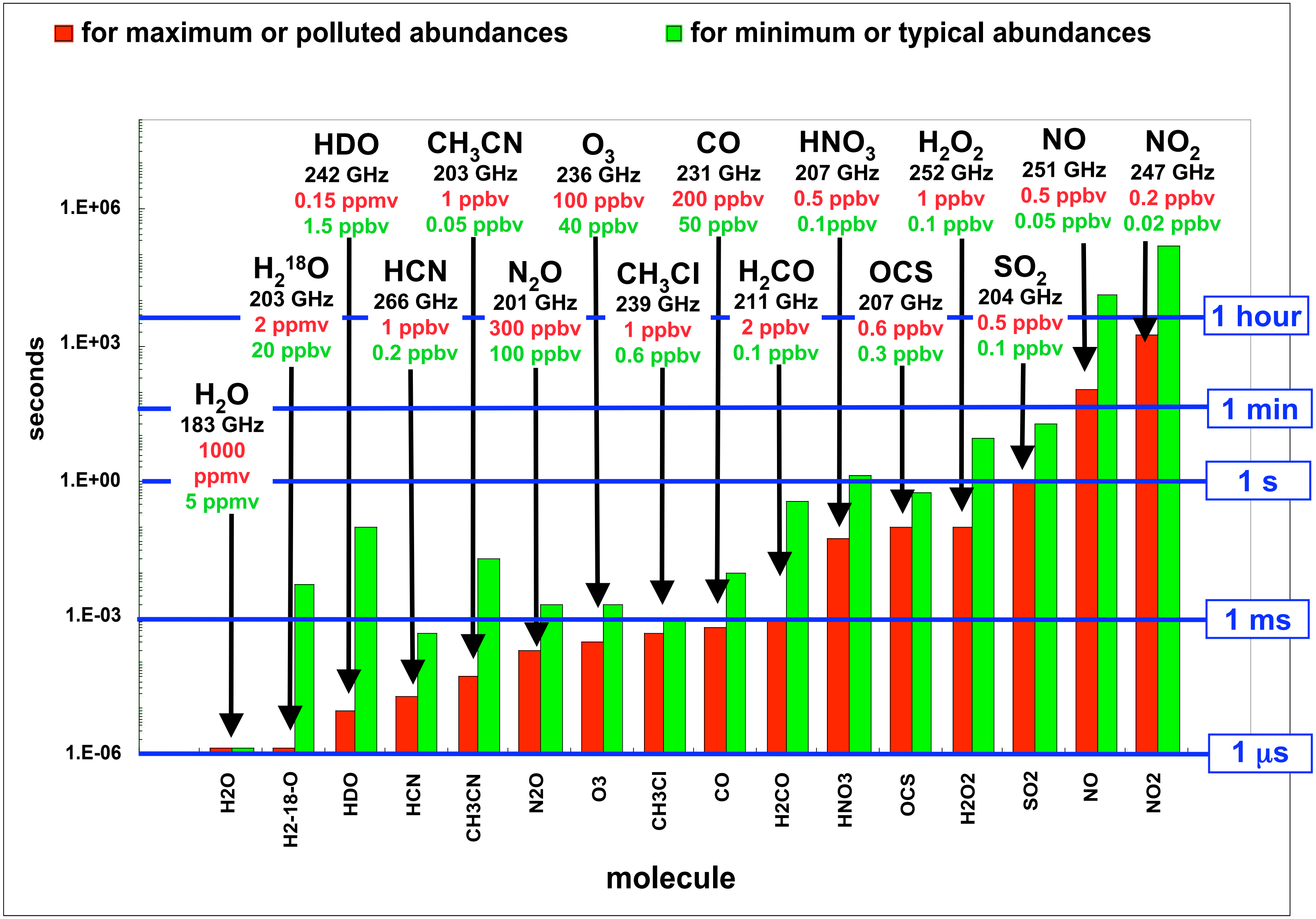
Initial estimate of cryocooler power budget for a 5-radiometer SMLS instrument



may be adequate to just have redundant drive electronics, in which case this load does not exist

- Science
  - New tropospheric chemistry measurement capability for regional and global phenomena and their couplings
  - Programmable measurement suite to respond to evolving science priorities and atmospheric events
  - Continue, in cost-effective way, MLS measurements needed for stratospheric chemistry and climate research
- Instrument: ‘Scanning MLS’ (SMLS)
  - Azimuth, as well as vertical, limb scanning
  - Radiometers using broadband and cooled mm/submm devices (enabling technology, along with flight cryocoolers)
  - Tunable local oscillators

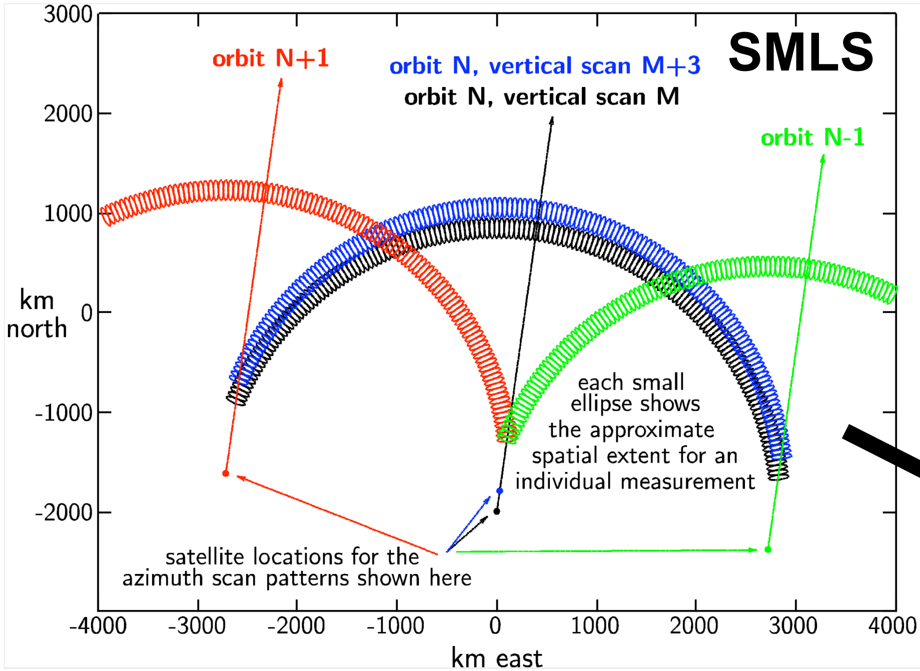
Measurement time required for spectral line S/N=10 for some upper tropospheric chemical species



Spatial Coverage

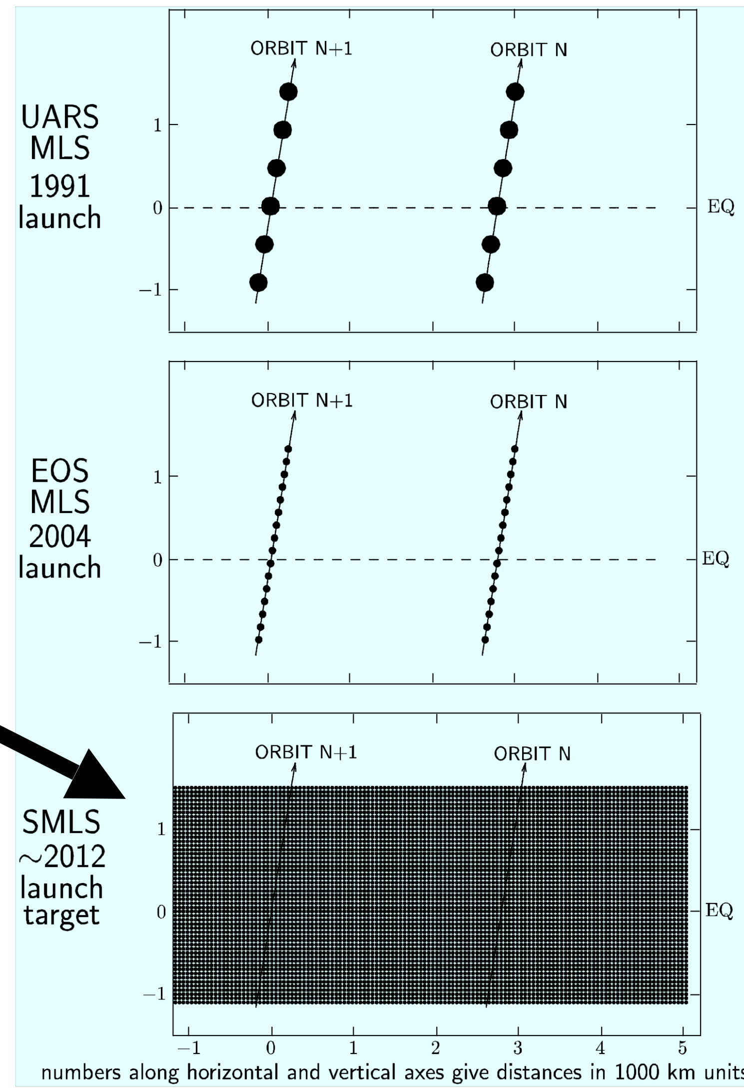
SMLS azimuth and vertical scans are each programmable; one example shown below for portions of adjacent orbits near equator

- **complete vertical scan (say 20 samples) every ~10s**
- **complete azimuth scan every ~0.5s, with cal**
- **measurements every ~2 ms (~50x50km horiz)**



- **We have yet to decide for sure whether az scan will extend all way to suborbital paths of adjacent orbits, as shown above, or az scans will just 'touch' at ends**
- **With such a scan, overlapping measurements (in nearly-orthogonal directions) from adjacent orbits can overcome line-of-sight resolution limitations**

SMLS compared with UARS and EOS MLS



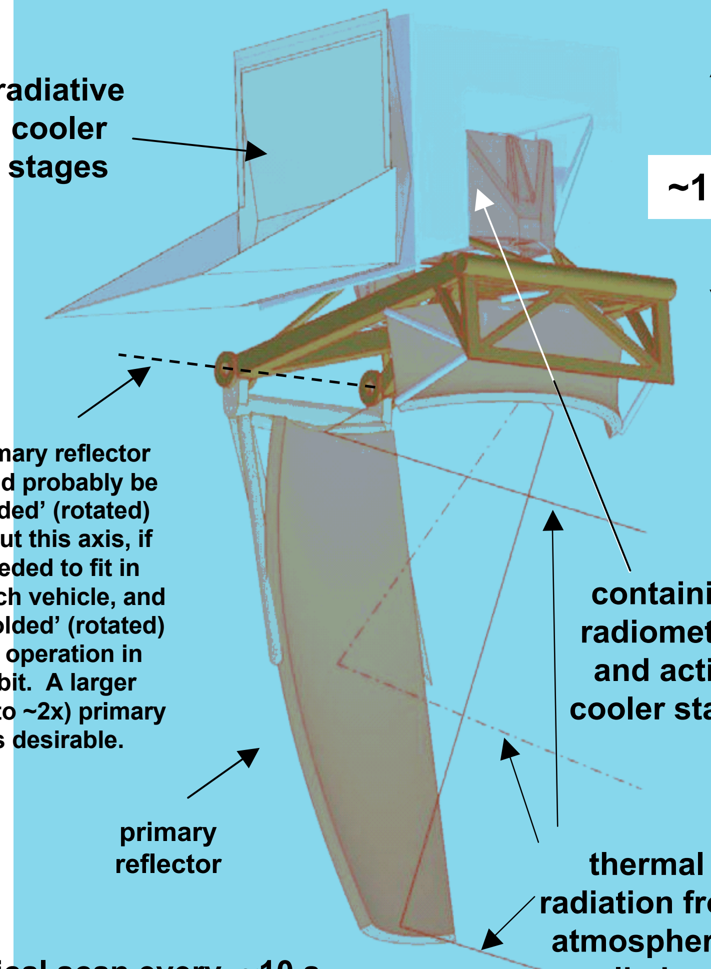
Summary of concept for 3rd-generation MLS

Science

- New capability for atmospheric chemistry measurements on regional and global scales
  - Measurements in presence of clouds/aerosol that cannot be done by other techniques
  - Complete daily (both day and night with no gaps) global coverage from low Earth orbit
- Cost-effectively continue measurements for stratospheric chemistry and climate research
- Programmable measurement suite (and scan) for easily responding to evolving scientific priorities and atmospheric events

Instrument: ‘Scanning MLS’

spectrometer module not shown



vertical scan every ~10 s
azimuth scan every ~0.5 s
measurement every ~0.002 s
data rate < 10 Mb/s

Summary & Future Efforts

- **An instrument with cryogenic receivers would give ~30 fold improvement in sensitivity over present instruments.**
  - Or 900 fold reduction in required integration time
- **We have a viable thermal/mechanical concept requiring for only:**

  ~40 watts for cooling the cryostat

  10 to 25 watts for cooling each radiometer.
- **Effort underway to study code-S cooler development for Earth Science applications such as described here. Extension from 6 to 4 Kelvin required**

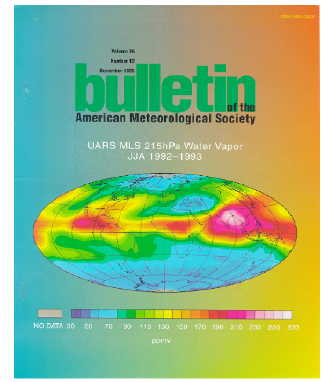
Future Efforts (continued)

- **Continue front end development.**
- **Calibration, not sensitivity, big hurdle for achieving sub 100 mK measurements in the presence of strong lines.**
  - Need to develop new calibration techniques
  - Need spectrometers with high linearity, flat spectral response, and > 2 GHz BW. Probably digital.
- **Large (3- 4 meter) antenna**
  - Mass becomes driving issue

Following are backup

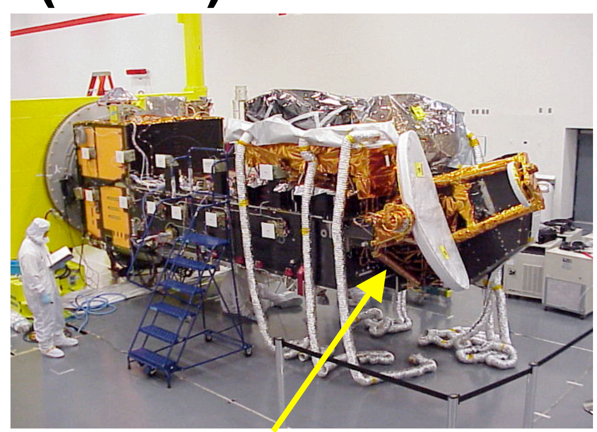
- **1st-generation: UARS MLS (1991)**
  - primarily for stratospheric chlorine chemistry
  - first microwave limb sounding from space, preceded by our aircraft and balloon experiments
  - 235 peer-reviewed MLS-related publications to date (listing at http://mls.jpl.nasa.gov)

O_3-destroying ClO



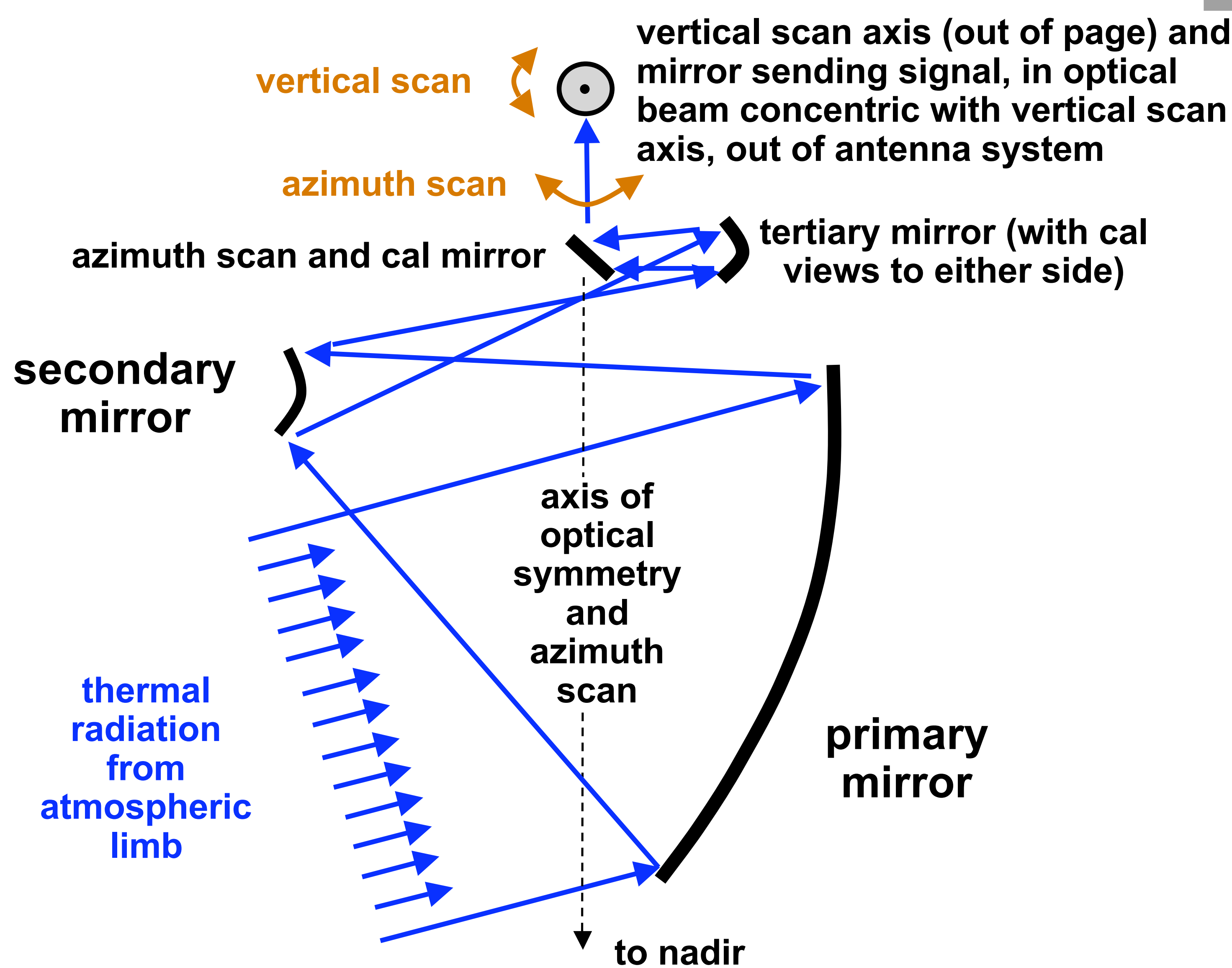
upper trop H_2O

- **2nd-generation: EOS MLS (2004)**
  - primarily for stratospheric chemistry and climate: important new measurements (OH, HO_2, BrO, ...) not possible with UARS
  - enabling technology: JPL planar devices which allowed measurements throughout the submm wavelength range



EOS MLS on Aura spacecraft

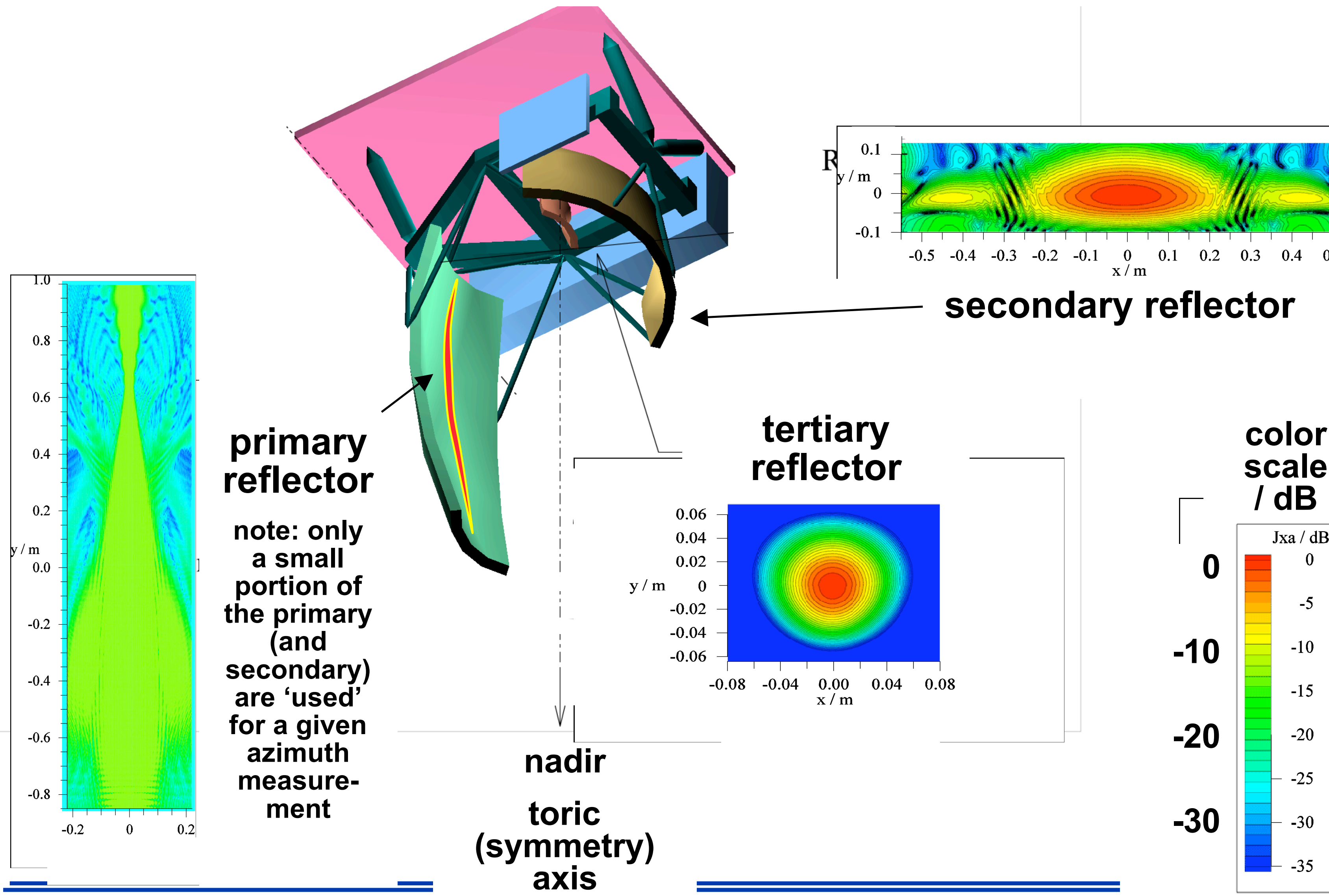
Toric Antenna Concept Applied to Azimuth Scanning of Limb



SMLS antenna concept & physical optics analyses

documented in Rick Cofield, Tom Cwik, and Nasrat Raouf's paper in proceedings of Aug 2002 SPIE meeting on 'Highly Innovative Space Telescope Concepts'

colors show current on each reflector for system considered as transmitter



- **Scan period**
  - For along-track sampling equal to cross-track sampling, must perform a vertical scan in the time the satellite moves the sampling distance

$$T_{scan} = \frac{\Delta s}{v_{sat}} = \frac{\Delta s}{6.8\,km/s}$$

  - 50 km sampling gives 7.4 s scan period for 700 km orbit (~10 s with retrace) Note: ~ 3 km/s (at limb) vertical scan rate gives vertical tangent point locus
- **Integration time**
  - Let's consider extreme example where we do an azimuth scan over ± 75^o, to give global coverage with nearly-orthogonal views. Dividing this 150^o total range into 50 km (1^o) wide segments gives 150 points in each azimuth scan.
  - Also let's consider a scan with 20 samples in the vertical
  - With a vertical scan period for 50 km along-track sampling, this gives an integration time per individual measurement sample of
    - 7.4s / (150 az x 20 vertical samples) = 2 msec